SWITCH-MODE POWER SUPPLIES

Recent advances in power semiconductor technology and inductive components have boosted the use of compact, high efficiency power supplies of the switch-mode type. Now SMPSs of various power ratings are becoming widely available at reasonable prices, it seems timely to focus on their design principles and practical aspects.

Most electronic circuits can not work without a power supply of some kind. The basic mains supply consists of a transformer, a rectifier, a filter (smoothing/reservoir capacitor), and a linear control circuit (regulator) for adjusting the output voltage to the desired value. It may be argued that the basic power supply has a number of important disadvantages. For relatively high powers, the mains transformer is often bulky and expensive, and the same goes for the smoothing capacitor(s). Moreover, the product of the voltage drop across the regulator and the current consumption of the load forms dissipated, and therefore wasted, power, which results in a very low overall efficiency, especially at relatively low output voltages. Not surprisingly, in the rapidly expanding world of microelectronics there arose a growing need for a high-efficiency power supply.

This need was met by the switch-mode power supply (SMPS), in which the output power is not regulated continuously, but pulsed at a relatively high frequency. An output filter is included for smoothing the supply voltage.

The filter components can be kept small thanks to the high frequency, and the same goes for the (toroidal) transformer if galvanic insulation is required.

Basic configurations

A switch-mode power supply is essentially a DC-DC converter. The 3 basic circuit configurations are shown in Fig. 1. The **flyback circuit** works as follows. A magnetic field builds up in the inductor as long as the switch remains closed. When the switch is opened, the inductor functions as an energy source. The voltage across the inductor is reversed, and the conducting diode passes the energy to the reservoir capacitor. Note that the output voltage is reversed with respect to the input voltage.

The **forward converter** does not reverse the polarity of the input voltage. The capacitor is charged via the inductor when the switch is closed. The difference between the input and the output voltage is available on the inductor. In contrast to that in the flyback converter, the switch is closed when the capacitor is being charged. When the switch is opened, the magnetic field of the inductor is weakened via the flyback diode. The switch is, of course, a power transistor, and the diode affords protection against the induced voltage. In a forward converter, the input voltage is higher than the output voltage.

The third basic configuration is referred to as **boost** or **step up** converter. This circuit increases the input voltage, and is functionally similar to the flyback converter. Energy is stored in the inductor when the switch is closed. When the switch is opened, this energy is supplied to the load at the output via the diode.

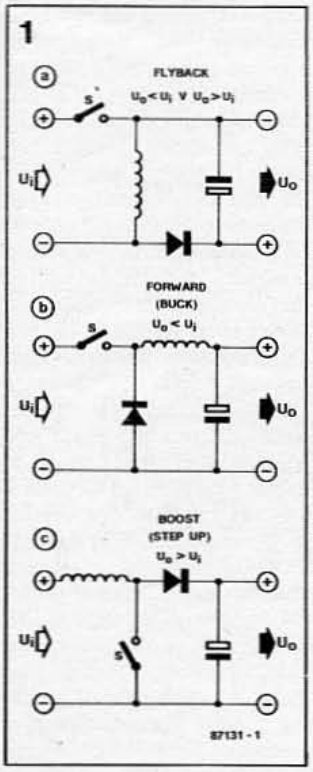

Fig. 1 The 3 basic configurations of a switch-mode power supply.

The continuous and discontinuous mode

Two modes of operation can be distinguished, depending on the current in the inductor—see Fig. 2.

After closing the switch, the current in the inductor increases linearly up to a specific maximum value (U_i = constant). After opening the switch, the current decreases linearly. The circuit operates in the *discontinuous current mode* if the current is nought in every period. The capacitor supplies the load current during the remainder of the period. The discontinuous mode is characterized by the good response of the closed regulation circuit to fluctuations in the input voltage (*line regulation*), and the output load (*load regulation*). There is no energy in the inductor at the start of each period, and regulation can, therefore, take place on a period-to-period basis. It can, in fact, be argued that the inductor is not present in the regulator circuit. The maximum phase shift of 90° in the buffer capacitor ensures the stability of the closed regulation circuit. A disadvantage of the discontinuous mode is the relatively high peak current carried by the power switch. Flyback and step up converters usually operate in the discontinuous mode.

In the *continuous current*

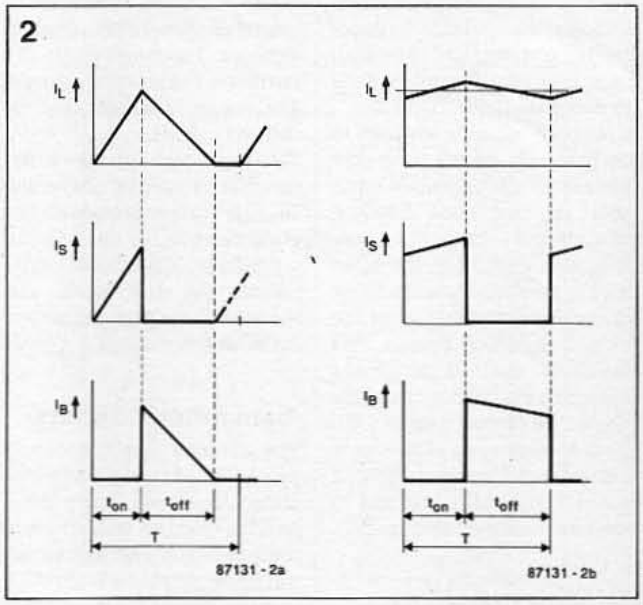

Fig. 2 The discontinuous (a) and the continous current mode (b) differ in respect of the current carried by the inductor.

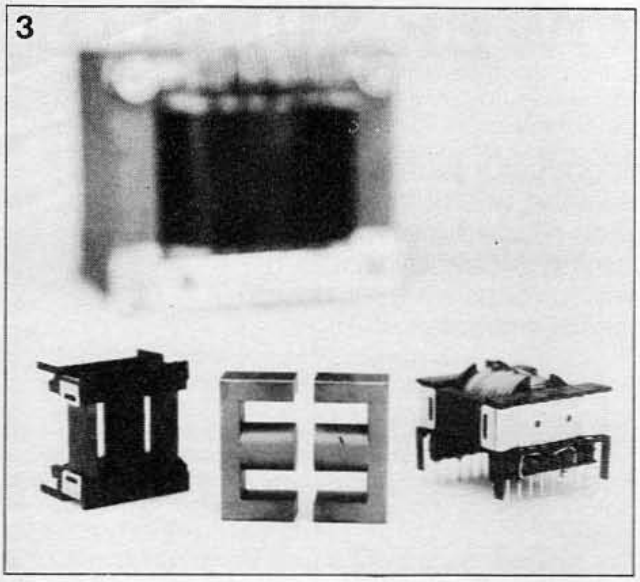

Fig. 3 A traditional soft iron core (background) and a modern ETD ferrite core of equal power rating.

mode, the current through the inductor does not drop to nought at the end of every period. The ripple current in the inductor is small relative to the load current, and this requires a fairly high self-inductance. The buffer capacitor, on the other hand, can be kept relatively small. The favourable shape factor of the current through the power transistor and the diode makes the continuous mode eminently suitable for high power applications. The response to load fluctuations is, however, worse than that of a circuit in the discontinuous mode. Each change in the output load current requires a corresponding change in the direct current through the (relatively large) self-inductance, and this process may take several periods to complete.

It is not possible for a system to automatically switch from continuous to discontinuous operation, or vice versa, because this would cause a considerable change in the open loop transfer characteristics, giving rise to instability of the closed regulation system. This means that the load current of a system in the continuous mode should be higher than half the peak-to-peak value of the ripple current in the inductor. Forward converters usually operate in the continuous current mode.

Off-line operation

In many cases, the input voltage is a rectified and smoothed voltage obtained direct from the mains. The direct voltage so obtained (approx. 335 V at a 240 VAC mains supply) is rarely used for converting down to, say, 12 V, in view of the resultant low duty factor, and the need for large self-inductances. Also, a direct connection to the mains is dangerous, and normally not permitted. This calls for a (ferrite) transformer, which, in an SMPS, has the advantage of being much smaller than a soft iron type used in the traditional 50 Hz mains supply (see Fig. 3). There are, however, a number of important considerations as to keeping the losses of the core material within acceptable limits. Ferrite is used instead of laminated iron, and offers a number of advantages. The construction of a ferrite core is relatively simple, and ferrite is a light and insulating material.

The turns ratio of the ferrite transformer enables converting the high input voltage down to a value close to the desired output voltage. The conversion increases the duty factor, and hence reduces peak currents in the power transistors.

Transformer circuits

The simplest configuration of an SMPS is the single transistor flyback converter shown in Fig. 4a. This circuit is well-known in low power supplies with an output rating up to about 250 W. In this application, the transformer is more properly referred to as a coupled self-inductance, because it assumes the function of the inductor shown in Fig. 1a. The forward converter in continuous mode is more suitable for feeding relatively heavy loads. The most commonly found version is based on a single transistor and a demagnetization winding in the primary circuit—see Fig. 4b. The transistor must be able to handle twice the input voltage. The demagnetization winding can be omitted if the circuit is extended with a transistor and a flyback diode as shown in Fig. 4c. In this circuit, the transistors need only withstand half the voltage. They are, however, driven with respect to different potentials, just as in the bridge circuits to be discussed.

Half or full bridge circuits are used mainly for high power applications. The full bridge variant is suitable for very heavy loads thanks to the fact that the effective input voltage is doubled. The last variant, shown in Fig. 4g, is also a bridge circuit, based on a centre-tapped transformer that enables the transistors to be driven with respect to a common reference potential.

Bipolar transistors as well as power FETs can be used in the primary circuit. Bipolar technology is suitable for switching frequencies up to 50 or 100 kHz. Power FETs are faster, and can be used at higher frequencies without running into excessive switch losses. Currently, the maximum usable frequency is about 1 MHz, and power FETs are expected to become predominant in SMPSs in view of the ever increasing switching frequencies. Power FETs for relatively high voltages are, however, still quite expensive, and more attractive for use in countries with a 117 V mains supply, such as the USA.

Core saturation

Any transformer winding forms a self-inductance, and the average voltage across it should, therefore, be nought. When this is not so, the remaining direct voltage causes an linearly increasing direct current until the core is saturated. The

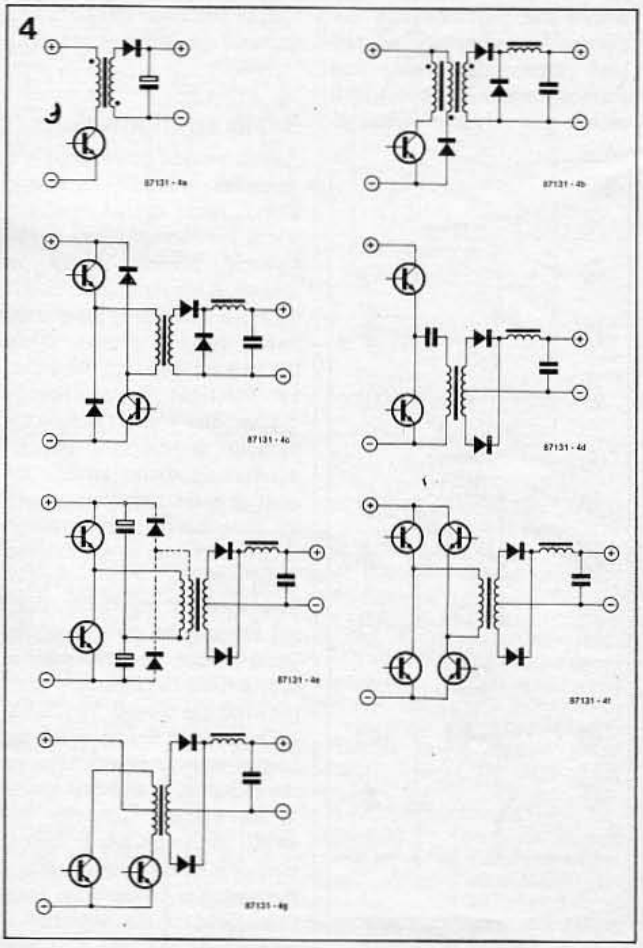

Fig. 4 Various configurations of the switching power stage in an SMPS.

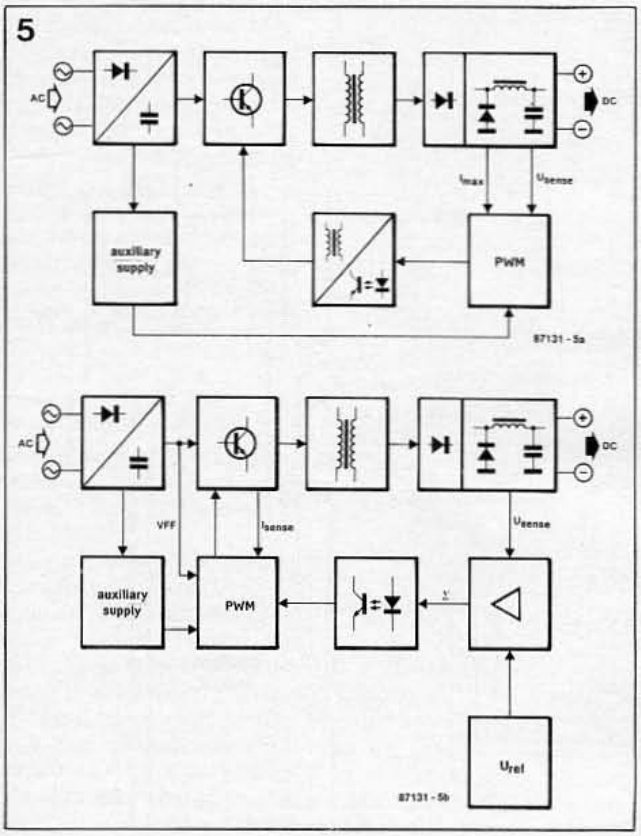

Fig. 5 Functional diagram of a SMPS with the control electronics located at the secondary side (a) or the primary side (b).

H-field, and with it the current, then increases exponentially, in accordance with Faraday's law of constant increase of the magnetic flux per unit of time. This effect must be prevented because it can lead to destruction of the primary circuit.

In the circuits of Fig. 4b and 4c, the field in the transformer core is weakened with the aid of the flyback diode(s), but only as long as the duty factor remains below 50%. Problems owing to permanent magnetization are not expected to arise in the circuit of Fig. 4d, where the coupling capacitor ensures the absence of direct current through the primary winding. The situation is more complex in Fig. 4e.Although the primary winding is AC coupled, a direct voltage may still exist at the junction of the capacitors. This positive or negative potential may arise from less than perfect (i.e., unbalanced) driving of the power transistors, which may have different recovery times also. Unbalancing of the primary circuit can be prevented with the aid of a compensation winding and 2 flyback diodes.

A coupling capacitor for blocking the magnetizing direct current is rarely used in the circuit of Fig. 4f, because this is rated for very high power. Both the positive and the negative current in the primary winding are measured, and any difference between them is compensated by controlling the duty factor. This safety measure can be applied to the circuit of Fig. 4g also.

Voltage control

In a switch-mode power supply, the output voltage is measured, compared to a reference, and kept constant by controlling the duty factor of the drive signal applied to the power switches (i.e., transistors). The regulating effect of the control circuit depends on the open-loop characteristics of the system. The simplicity of the flyback converter makes it less suitable for many purposes, since the duty factor depends primarily on the load at a constant output voltage. Good voltage regulation requires a high amplification of the measuring and control circuit. In a forward converter, the voltage control circuit need not have a strongly regulating effect because in essence the output voltage depends only on the turns ratio of the transformer (assuming a constant input voltage).

There are 3 basic types of voltage control system:

- Direct duty factor control. The error signal is amplified, and drives a pulsewidth modulator, which in turn adjusts the duty factor as required. A high overall amplification is needed, at the cost of some stability—notably in the case of converters operating in the continuous mode.
- Voltage feedforward. This is the most commonly used system. Preregulation of the duty factor is implemented as a function of the input voltage, enabling the output voltage of the open loop system to be made independent of the input voltage. The control circuit is, therefore, only required for compensating load fluctuations. The preregulation system improves the line regulation, and so ensures sufficient suppression of hum.
- Current mode control. A second control circuit (inner loop) inside the voltage control circuit (outer loop) enables switching off the power transistor at a more or less fixed peak value of the current. The effect so obtained is the (quasi) disappearance of the inductor from the output filter. The whole system is then essentially a first order network with the capacitor in the output filter as the only phase changing element. The stability of the whole supply, as well as the response of the closed system to fluctuations in the input voltage and the load current, is excellent. High power forward converters of the continuous type are often equipped with a current mode control for obvious reasons.

Location of the control circuit

The voltage control circuit can be located at the primary or the secondary side of the supply. A circuit at the primary side (Fig. 5b) makes it possible to drive the power stage direct from the IC, while it is a relatively simple matter to implement circuits for primary current monitoring and preregulation. A disadvantage of the primary location is the need for an insulating device in the control loop for transmitting an analogue signal from the primary to the secondary side. This is usually done with the aid of an optocoupler. Only the error signal is transmitted to rule out instability of the output voltage owing to ageing effects in the optocoupler.

A control circuit at the secondary side (Fig. 5a) enables direct coupling of the voltage control circuit. Also, it allows the use of the the reference circuit built into many of the currently available integrated SMPS controllers. The PWM signal is fed to the power stage via a fast optocoupler, or a special pulse transformer. Differences in the drive applied to several power transistors are relatively simple to monitor and correct, but the primary location makes it difficult to keep tabs on the primary current.

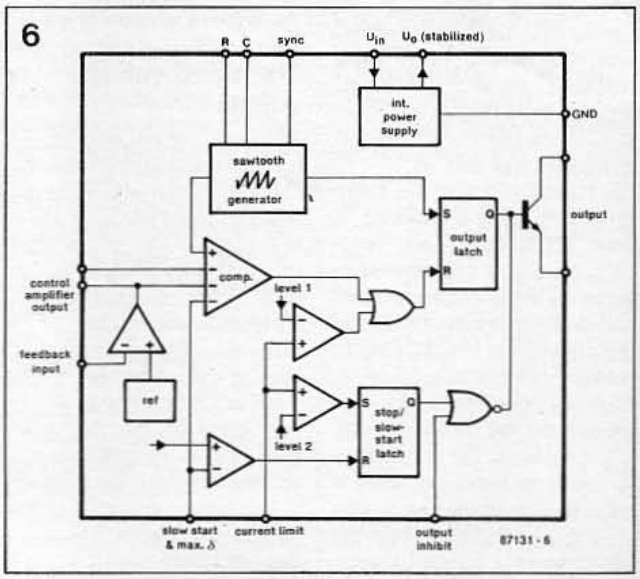

Fig. 6 General block diagram of an integrated SMPS controller.

Whatever control circuit is used, it must have its own (start) supply. The self-generated voltage is, of course, only usable after the supply is fully operational.

SMPS controllers

A wide variety of integrated circuits is currently available for controlling switch-mode power supplies. These ICs are essentially very similar, and a general block diagram is therefore given in Fig. 6 to explain their operation.

The pulsewidth modulator is composed of a sawtooth generator, a voltage comparator and a set-reset bistable. A second input on the comparator is connected to the output of an opamp that amplifies the difference between the real and the required (set) output voltage. An accurate, and temperature compensated, voltage reference is often included for adjusting a specific output voltage.

The remainder of the circuits in the chip have auxiliary functions, and serve for various types of protection. Voltage feedforward or current mode control is possible by changing the slope of the sawtooth signal. Special control inputs make it possible to set a duty factor of nought. An analogue input is activated above a predefined voltage level, and can be used for making a 2-level short-circuit protection. When the output current reaches the first level, the duty factor is held constant, and the circuit supplies a constant, maximum, current. The duty factor is made nought above level 2. A digital input enables remote control of the supply (computer-controlled test sites, etc.).

An input for setting the maximum duty factor is standard on most SMPS controllers. Properly driven, it prevents saturation of the transformer core, and hence an exponentially rising primary current. This safety measure is especially useful for supplies operating in the continuous current mode. In these, the duty factor has a tendency to rise to the maximum value at each change in the output current, in an effort to correct the direct current through the inductor in the output filter in accordance with the new load.

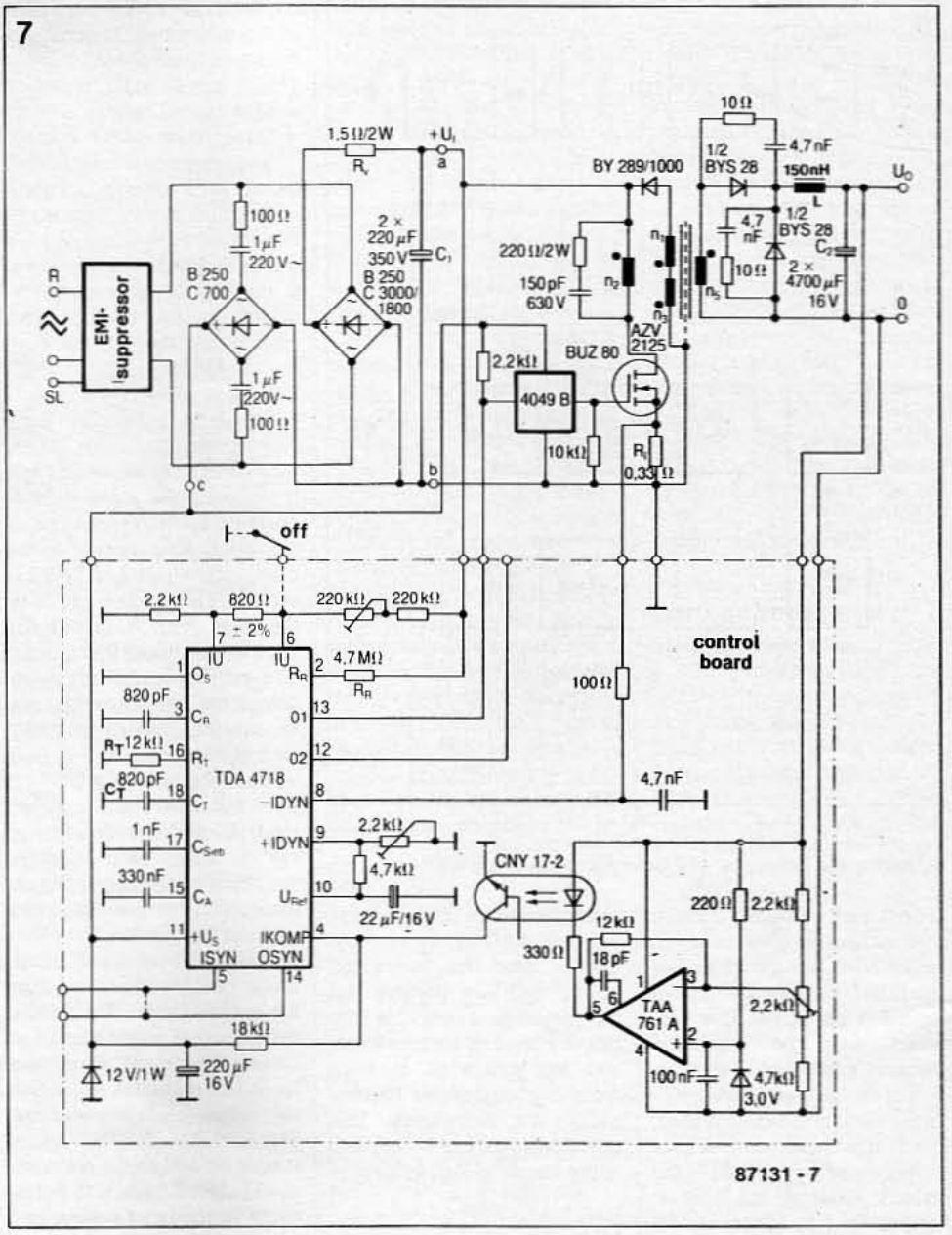

Fig. 7 Circuit diagram of a 5 V; 20 A; 50 kHz supply (courtesy Siemens).

The multi-voltage supply

Additional supply voltages are fairly simple to implement in a SMPS with the aid of appropriate auxiliary windings on the secondary of the transformer. In computer equipment, the usual combination is a powerful 5 V section, and auxiliary ±12 V supplies. Voltage control is usually only effected on the +5 V rail. If the magnetic coupling between the secondary windings on the transformer is sufficiently tight—this is typical of a well-constructed transformer—the output voltage of the auxiliary windings is regulated along with the main supply, at acceptable accuracy.

Losses

Switch-mode power supplies are known mainly for their high efficiency. In spite of this, some power is, of course, wasted.

- Switching losses in the power transistors. Faster switching—e.g. with the aid of a speed-up capacitor—keeps these losses acceptable. The power loss incurred in the conductive transistor is relatively small, especially at high input voltages.
- Transformer losses can be classified as copper or core losses. At switching frequencies below 100 kHz, copper losses are the main consideration in finding the optimum specifications of the transformer in the SMPS. Also, care should be taken to counter a considerable skin effect, which reduces the effective diameter of the copper wire as the frequency increases. Many SMPS manufacturers use litze wire for their transformers to prevent losses arising from the skin effect.

Core losses are due to eddy currents and hysteresis of the ferrite material. They depend on the so-called *flux density sweep*, and the frequency. Manufacturers of ferrite cores can supply graphs to establish the maximum permissible core losses as a function of the thermal resistance of the core, and other parameters. Core losses

form the crux in designing a transformer for use in an SMPS.

• Rectification and filter losses. These become more serious at relatively low output voltages (5 V), and are mainly due to the forward voltage drop across the diodes. Schottky diodes are often used in view of their low forward voltage drop and good switching characteristics. Some power is also wasted in the inductor as part of the output filter.

A practical circuit

The circuit diagram of a typical switch-mode power supply is shown in Fig. 7 (Siemens Application).

Buffer capacitor C_1 is fitted at the output of a bridge rectifier, which is fed from a mains filter. Power resistor R_V limits the peak charge current when the supply is switched on. The type of transformer used makes clear that the circuit is a forward converter. The primary and secondary winding (N_2; N_5) are in phase, as indicated by the dots. Auxiliary windings N_1 and N_3 serve to demagnetize the core. The dotted line in the core indicates the use of an electromagnetic shield. The configuration of the secondary output filter shows that the supply is designed for operation in the discontinuous current mode. A relatively small self-inductance is used in conjunction with a large buffer capacitance to ensure sufficient output power when the inductor carries no current. The output voltage is divided and compared to a 3 V reference. The error signal from the operational amplifier is fed to the TDA4718-based primary control circuit via an optocoupler. Components C_T and R_T define the switching frequency of 50 kHz. Provision has been made to set the maximum output current (pin 9). The maximum primary current is monitored with the aid of the network connected to pin 8. The capacitor fitted at pin 15 of the controller ensures a gradual increase of the duty factor after power-on (*soft start*). The input voltage is checked via pin 6 and 7. The duty factor is made nought when the input voltage is either too low or too high. Voltage feedforward is implemented with the aid of R_R, connected to pin 2. The switch signal at the output of the controller is fed to the power MOSFET via a number of parallel CMOS buffers contained in a CD4049 package. The control circuit is fed from the mains via a capacitive voltage divider.

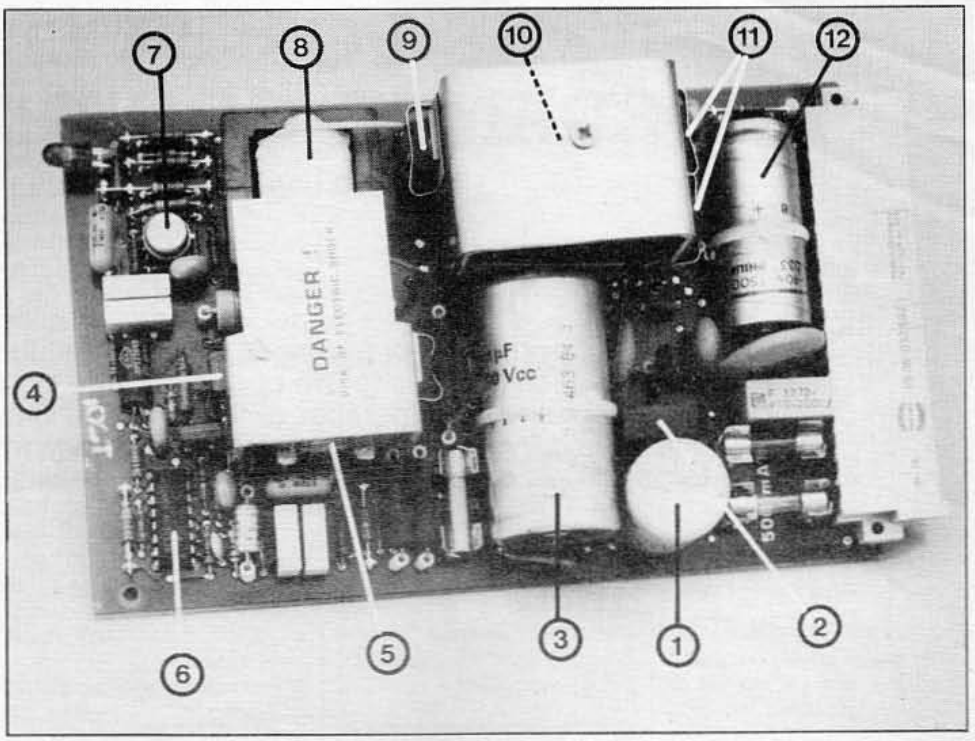

Fig. 8 A compact switch-mode power supply.

Figure 8 shows a compact SMPS fitted on a printed circuit board. The arrows point to the following, essential, parts: (1) mains filter; (2) primary rectifier; (3) buffer capacitor for primary voltage; (4) switching transistor; (5) pulse transformer for base drive; (6) SMPS controller for pulsewidth modulation; (7) (secondary) voltage reference and error amplifier; (8) ferrite core transformer; (9) primary flyback diode for weakening the transformer field; (10) inductor in output filter; (11) secondary rectifier and flyback diode; (12) output capacitor.

Further developments

The scope of this introductory article does not allow a detailed discussion of all the technical considerations that go into designing a switch-mode power supply. In a forthcoming issue of *Elektor Electronics* the subject will be reverted to in the context of a construction project.

The theoretical aspects of the SMPS have been known for some time, but it was not until the coming of fast power transistors, integrated controllers and new ferrite materials that serious development of the SMPS was launched. Ever higher switching frequencies make it possible to reduce the size of the secondary filter, but at the same time pose a real difficulty as regards electromagnetic interference (EMI) due to the often large number of strong harmonics and other spurious products. It is with this in mind that there is a growing interest in free-running supplies, in which the currents are sinusoidal rather than rectangular. Meanwhile, supplies of the types discussed in this article are constantly reworked and enhanced to make the current consumption from the mains sinusoidal. This ensures less interference on the mains, a higher efficiency of the rectifier thanks to the more favourable shape factor of the current, and reduced peak currents in the buffer capacitor(s).

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For further reading:

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- *Electronic Components & Applications. Vol. 2; No. 1*; Philips, November 1979.
- *Unitrode Switching Regulated Power Supply Design Seminar Manual*; Unitrode, ed. 1986.
- *Schaltnetzteile (SNT), Technik und Bauelemente*; Siemens Technische Mitteilung No. B9-B3269.
- *Steuer und Uberwachungsschaltungen fuer moderne Schaltnetzteile (SNT), TDA47xx Familie*; Siemens Technische Beschreibung No. B/3132.
- *Integrierte Schaltnetzteil-Steuerschaltungen, Funktion und Anwendung*; Siemens Technische Beschreibung No. B1-B3116.
- *SGS power supply application manual*; July 1985.
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